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Mixing and segregation of solid particles in a conical spouted bed: Effect of particle size and density

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ABSTRACT

In this work, the mixing and segregation of binary mixtures of particles with different sizes and densities in a pseudo-2D spouted bed were studied experimentally. A binary mixture of solid particles including sand, gypsum, and polyurethane was used. To determine the particles mass fraction, and their mixing and segregation in the bed, an image-processing technique was developed and used. Important hydrodynamic parameters, such as the axial and radial segregation profiles of the solid particles, were measured. The effects of air velocity, particle size, and particle mass fraction were also evaluated. The flow regime in the spouted bed and the time required for reaching the equilibrium state of the solid particles were discussed. The results showed that the segregation of solid particles and the time to equilibrium both decreased when the air velocity increased to much larger than the minimum spouting velocity. The axial segregation increased with the diameter ratio of the particles. Upon completion of the test, coarse particles were concentrated mainly in the spout region, while fine particles were aggregated in the annulus region. Examination of the flow pattern in the spouted bed showed that the particles near the wall had longer flow paths, while those near the spout region had shorter flow paths.

Introduction

Spouted beds are efficient air–solid mixers in which particles are thrown upward by high-velocity airflow through an orifice at the base of a column. These beds provide effective air–solid contact, especially for large and dense particles. Spouted beds have been successfully used in various processes, such as the drying of beans, slurries and pastes, granulation, the coating of particles, aerification, pyrolysis, and combustion (Epstein & Grace, 2011). One main advantage of conical spouted beds is short air residence times with a narrow distribution (Olazar, San Jose, & Bilbao, 2011). To make more effective use of conical spouted beds in industrial facilities, an improved fundamental understanding of their hydrodynamics is required. Mixtures of solid particles of different sizes and/or densities tend to separate during fluidization in spouted beds. The mixing and segregation of the particles are often of great importance because these processes influence the quality of fluidization.

In the past, many experimental studies have been performed to better understand the behavior of spouted beds (Altzibar et al., 2008; He, Lim, Grace, Zhu, & Qin, 1994; He, Qin et al., 1994; Olazar, San Jose, Izquierdo, Alvarez, & Bilbao, 2001; Zhao, Li, Liu, Song, & Yao, 2008). Numerical simulation is also a useful tool for studying the important mechanisms in spouted beds. In recent years, computational fluid dynamics (CFD) has gained popularity for analyzing dense gas–solid two-phase flows. For spouted beds at ambient conditions, the air–solid flow behavior has been studied using the two-fluid model (TFM) approach (Du, Bao, Xu, & Wei, 2006; Duarte, Olazar, Murata, & Barrozo, 2009; Hosseini, 2016; Hosseini, Ahmadi, & Olazar, 2013; Hosseini, Ahmadi, & Olazar, 2014; Hosseini, Fattahi, & Ahmadi, 2015; Jiang, Zhong, Liu, & Jin, 2014; Liu et al., 2013; Liu, Zhong, Shao, Ren, & Jin, 2014; Zhong et al., 2013). Ren, Zhong, Jin, Shao, and Yuan (2013) studied the mixing behavior of corn-shaped particles in a spouted bed. The results showed that the spouting air velocity and particle property were important parameters influencing the particle-mixing quality in spouted beds. The mixing quality is also found to be sensitive to particle shape; for example, spheres mix faster and more homogeneously than corns. Saidi, Tabrizi, Grace, and Lim (2015) studied the hydrodynamics of rectangular spout-fluid beds using the computational fluid dynamics–discrete element method (CFD–DEM). The effects of 2D and 3D CFD modeling on the pressure drop, air velocity, particle flux, and voidage profiles in different directions were compared in a column with a

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thickness of 30 mm. The results showed that the bed thickness and the CFD modeling dimensions affected the predicted flow.

The spouting of fine particles is significantly different from that of coarse particles, and a stable spouting can be obtained only under constrained operating conditions. However, the stability of a spouted bed with fine particles can be effectively improved by the addition of coarse particles (Du et al., 2015a). In past studies, research efforts were mainly focused on improving the spouting stability for fine-particle systems for applications as chemical reactors. One promising approach is the addition of coarse particles to spouted beds of fine particles.

Zhang, Zhong, Jin, and Xiao (2012, 2013) investigated the effects of the mixing index, particle size, and particle density on spouting in a flat-bottom spouted bed. Ren et al. (2012) studied the mixing behavior in spouted beds and found that the mixing process for binary mixtures had three phases: macro-mixing, micro-mixing, and stable mixing. Du et al. (2015b) studied the effects of particle size, density, mixing ratio, air velocity, and nozzle diameter on the flow regime transition and minimum spouting velocity in spouted beds. Their results showed that a moderate increase in the mean particle diameter and density caused by the addition of coarse particles was beneficial to the spouting stability. In a continuation of their study, Du et al. (2015a) investigated the pressure drop and the pressure fluctuation signals and their connections to the mechanisms of flow regime transitions in spouted beds with binary mixtures. In addition, they described the influence of differences in the particle size and density on the spouting stability using power-spectral analysis.

A survey of the literature shows that several experimental tools have been used to study flow regime transitions. These include optical fiber endoscopy (Chen et al., 2013; Qian et al., 2013), particle image velocimetry (Liu, Li, Zhao, & Yao, 2008; Zhao et al., 2008), and fiber optic probes (Johnsson & Johnsson, 2001; Link et al., 2009). Each technology, however, has its inherent limitations. Recently published papers indicate that imaging techniques are becoming a popular method for measuring particle concentrations in 2D gas–solid flows. Early applications of imaging techniques often gave only qualitative observations of the flow behavior. However, digital image-processing techniques have provided the capability for imaging techniques to provide simultaneous measurements of particle velocities and concentrations as well as the size and shape of particles (Chen et al., 2013).

The above literature survey shows that the application of spouted beds with binary mixtures to large-scale industrial processes encounters many challenges. This is mainly because of the lack of a comprehensive understanding of the flow regime transition, which is quite different from that of a single-sized particle system. In this study, the mechanism of the flow regime transition of spouted beds with binary mixtures was investigated experimentally with the use of image analysis techniques. The effects of the solid mass fraction, air velocity, and particle size ratio on the particle mixing in conical spouted beds were studied. Binary particle mixtures with different densities and sizes were evaluated. The axial distributions of solid particles differing in size and density were measured for various velocities. The flow patterns and solid motion in spouted beds at different air velocities and with different binary mixtures were analyzed. The effect of the spouting air velocity on the mixing process was also studied.

Experimental

Apparatus

The experiments were carried out in a conical spouted bed. The bed consisted of a rectangular column, with cross-sectional dimensions $\alpha = 15$ cm and $\beta = 2$ cm and a conical section with inclined angle of $\theta = 120^{\circ}$ and height $l_c = 11.5$ cm. The physical parameters of the bed are listed in Table 1 and a schematic of the bed is shown in Fig. 1.

Table 1
Experimental condition of the conical spouted bed.

Column width, α (cm)	15
Column thickness, β (cm)	2
Overall bed height, δ (cm)	90
Slot width, λ (cm)	2
Conical section height, l_c (cm)	11.5
Height of the inlet port, l_p (cm)	2

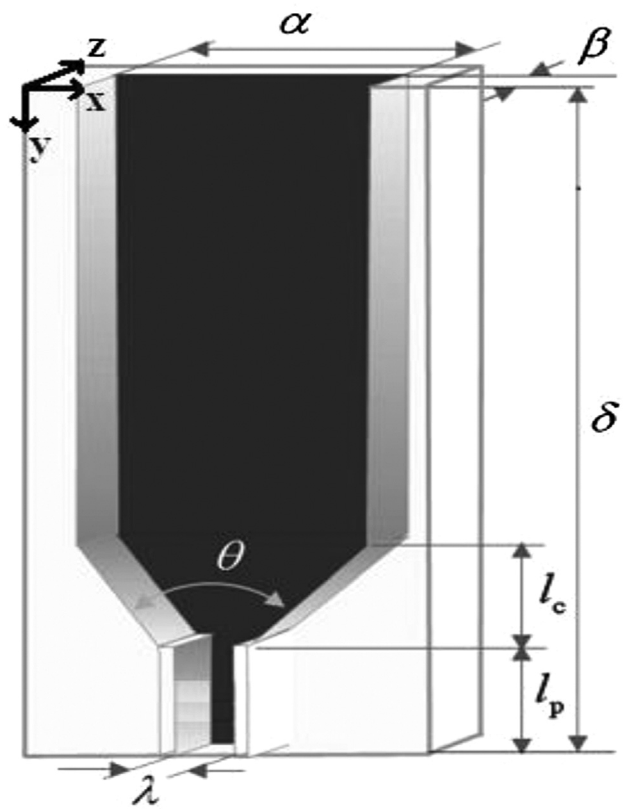

Fig 1. Schematic of the experimental spouted bed.

A schematic diagram of the experimental apparatus, including the measurement equipment, is shown in Fig. 2. Accordingly, air was supplied by a compressor and passed through air filters before entering the spouted bed. The airflow rate was measured by a rotameter. Images of the solid flows in the spouted bed were recorded using a high-speed camera (Canon EOS kiss F, 2592 × 3888-pixel resolution and 1/3200 shutter speed). To obtain a clear visualization, two identical 500-W fluorescent lights were symmetrically placed near the spouted bed to illuminate the flow field.

Materials

The experiments were performed using air at room temperature and atmospheric pressure. Sand, gypsum, and polyurethane were used as the test materials in this study. The diameters of spherical particles were measured using calipers and the average particle diameter was calculated. The mean diameters of irregular particles were determined with use of sieve analysis. The physical properties of the particles are summarized in Table 2. The density and